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Neutralino Cold Dark Matter in a One Parameter Extension of the Minimal Supergravity Model

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Within the minimal supergravity model (mSUGRA) framework, the expectation for the relic density of neutralinos exceeds the WMAP determination, unless neutralinos *a*) have a significant higgsino component, *b*) have a mass close to half that of a heavy Higgs boson, or *c*) can efficiently co-annihilate with a charged or colored particle. Within a 1-parameter extension of the mSUGRA model which includes non-universal Higgs masses, we show that agreement with the WMAP data can be obtained over a wide range of mSUGRA parameters for scenarios *a*) and *b*), so that the phenomenological implications may be much more diverse than in mSUGRA. We show that direct and/or indirect detection of neutralino dark matter should be possible at various current and planned facilities.

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Supersymmetry (SUSY) is a novel spacetime symmetry between bosons and fermions. In realistic models, SUSY is broken at the weak scale implying that all Standard Model (SM) particles must have superpartners with masses in the range $\sim 100-1000$ GeV that will be accessible to colliders. The lightest neutralino $\widetilde{Z}_1$ of R-parity conserving SUSY models is an especially attractive and well-motivated candidate for cold dark matter (CDM) in the universe[1]. The WMAP collaboration[2] has recently determined the relic density of CDM in the universe to be $\Omega_{CDM}h^2 = 0.113 \pm 0.009$ (1σ); this measurement, especially its implied *upper limit*, provides a powerful constraint for any model of particle physics that includes a candidate for CDM.

The present neutralino relic density can be determined by solving the Boltzmann equation for neutralinos in a Friedmann-Robertson-Walker universe. The central aspect of the calculation involves a computation of the thermally averaged neutralino annihilation and co-annihilation cross sections. Many analyses of SUSY CDM have been carried out within the paradigm minimal supergravity (mSUGRA) model[3]. The free parameters of the mSUGRA model consist of m_0, $m_{1/2}$, A_0, $\tan\beta$, and $sign(\mu)$, where m_0 is the common scalar mass, $m_{1/2}$ is the common gaugino mass, and A_0 is a common trilinear soft SUSY breaking parameter all defined at the scale $Q = M_{GUT} \simeq 2\times 10^{16}$ GeV. The parameter $\tan\beta$ is the ratio of weak scale Higgs field vacuum expectation values, and μ is a superpotential parameter whose magnitude is constrained by the requirement of radiative electroweak symmetry breaking (REWSB). Once these model parameters are specified, then all sparticle masses and mixings are determined, and scattering cross sections, decay rates, relic density and dark matter detection rates may all be reliably calculated.

It has been increasingly recognized that the typical value of $\Omega_{\widetilde{Z}_1}h^2$ as given by the mSUGRA model significantly exceeds its WMAP upper limit. Only specific regions of the mSUGRA model parameter space where neutralinos can efficiently annihilate are in accord with the WMAP data. These include: *i*) The bulk annihilation region at low values of m_0 and $m_{1/2}$, where neutralino pair annihilation occurs at a large rate via t-channel slepton exchange. *ii*) The stau (stop) co-annihilation region at low m_0[4] (for special values of A_0[5]) where $m_{\widetilde{Z}_1} \simeq m_{\tilde{\tau}_1}$ ($m_{\widetilde{Z}_1} \simeq m_{\tilde{t}_1}$) so that $\widetilde{Z}_1$s may co-annihilate with $\tilde{\tau}_1$s ($\tilde{t}_1$) in the early universe. *iii*) The hyperbolic branch/focus point (HB/FP) region at large $m_0 \sim 3-7$ TeV (depending sensitively on the assumed value of m_t) near the boundary of the REWSB excluded region where $|\mu|$ becomes small, and the neutralinos have a significant higgsino component, which facilitates annihilations to WW and ZZ pairs[6]. *iv*). The A-annihilation funnel, which occurs at very large $\tan\beta \sim 45-60$. In this case, the value of $m_A \sim 2m_{\widetilde{Z}_1}$, so that neutralino annihilation in the early universe is enhanced by the A (and also H) s-channel poles[7]. These allowed regions frequently occur either at edges of parameter space, or for extreme values of mSUGRA parameters. In this paper, we show that mSUGRA parameter choices that were previously disallowed by WMAP can in fact be brought into accord with the relic density measurement via two possible solutions, in a well motivated one parameter extension of the model. Thus, parameter choices thought to be irrelevant for collider and other SUSY searches are in fact now allowed.

The assumption of a universal soft SUSY breaking scalar mass m_0 is phenomenologically motivated for matter scalars, since universality guarantees in a super-GIM mechanism which suppresses dangerous flavor changing neutral current processes[8]. Within the framework of gravity-mediated SUSY breaking, universality for *all* scalars is realized by assuming a flat Kähler po-

tential, though non-universal scalar masses are certainly possible[9]. While universal masses for matter scalars is phenomenologically motivated, there is, no motivation for assuming that the Higgs field scalars also have a common GUT scale mass m_0. Indeed, in supersymmetric $SO(10)$ grand unified theories, which are highly motivated by recent data on neutrino masses, the matter multiplets of each generation belong to the 16 dimensional spinorial representation of $SO(10)$, while the Higgs multiplets inhabit a single 10 dimensional fundamental representation, and would have an unrelated mass, assuming that the SUSY breaking mechanism is not completely blind to gauge quantum numbers. In the simplest case, we may naively expect the Higgs soft SUSY breaking squared masses to obey $m_{H_u}^2 = m_{H_d}^2 \neq m_0^2$ so that this one parameter extension is characterized by,

$$m_0,\ m_\phi,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{and}\ sign(\mu), \tag{1}$$

where $m_\phi = sign(m_{H_{u,d}}^2)\cdot\sqrt{|m_{H_{u,d}}^2|}$.[1] We dub this the *non-universal* Higgs mass (NUHM1) model, to distinguish it from the more general NUHM2 model[10, 11] where each Minimal Supersymmetric Standard Model (MSSM) Higgs scalar has an independent mass parameter at $Q = M_{GUT}$. The NUHM2 model has recently been investigated by Ellis et al.[12], and is motivated instead by $SU(5)$ SUSY grand unification. These NUHM2 models have also been investigated recently within the context of Yukawa unified SUSY models[13].

We begin our analysis of the NUHM1 model by noting that the parameter range for m_ϕ need not be limited to positive values. Some authors have invoked the so-called GUT stability bound, $sm_\phi^2 + \mu^2(M_{GUT}) > 0$ (with $s = sign(m_\phi)$), to avoid EWSB at too high a scale; see Ref. [14] where the applicability of these bounds is discussed. Except to note that these are hardly constraining for the cases that we present here, we do not consider them any further.

We generate sparticle mass spectra using ISAJET v7.72[15] upgraded to allow the input of negative Higgs squared masses. ISAJET includes full one-loop radiative corrections to all sparticle masses and Yukawa couplings, and minimizes the scalar potential using the renormalization group improved effective potential renormalized at an optimized scale choice to account for leading two loop terms. We evaluate the relic density using the

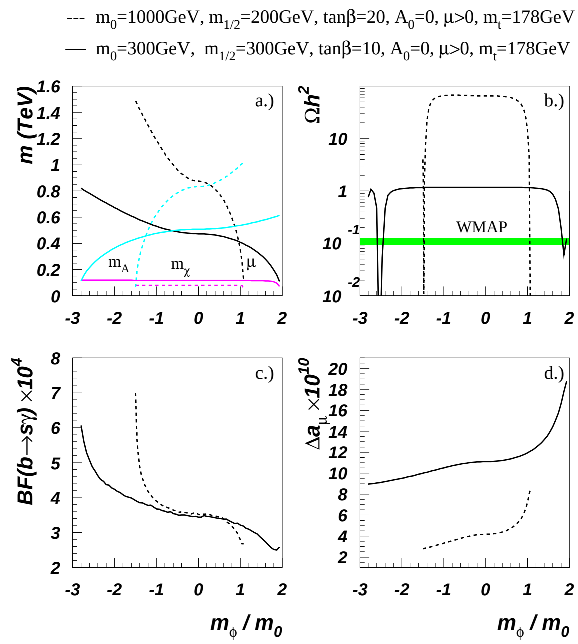

FIG. 1: The values of a). μ, m_A and $m_{\widetilde{Z}_1}$ versus m_ϕ/m_0 for two cases in the NUHM1 model. We also show b). $\Omega_{CDM}h^2$, c). $BF(b\to s\gamma)$ and d). Δa_μ. The curves terminate on the left (right) because $m_A^2 < 0$ ($\mu^2 < 0$) so that REWSB is not obtained.

IsaReD[16] program, and to evaluate the indirect CDM signals expected from the NUHM1 model, we adopt the DarkSUSY[17] package interfaced to ISAJET.

As a first example, in Fig. 1 we show one of the critical aspects of the NUHM1 model, where we plot in a) the values of μ, m_A and $m_{\widetilde{Z}_1}$ versus m_ϕ/m_0, while fixing other parameters as listed. One can see that μ becomes much larger for $m_\phi \leq -m_0$, and much smaller for $m_\phi > m_0$ compared to the case of $m_\phi = m_0$. The region of small μ is of particular interest since in that case the lightest neutralino becomes more higgsino-like, and gives rise to a relic density which can be in accord with the WMAP determination[18]. In the mSUGRA model, the higgsino-like $\widetilde{Z}_1$ region occurs in the HB/FP region mentioned above, with $m_0 \sim 3-7$ TeV. We immediately see one important virtue of the NUHM1 model: the higgsino annihilation region may be reached even with relatively low values of m_0 and m_ϕ. Thus, unlike the mSUGRA model case, the low $|\mu|$ region of the NUHM1 model can occur for small values of m_0, m_ϕ and $m_{1/2}$, and so need not suffer from fine tuning[19].

We also see from Fig. 1 that the value of m_A can range beyond its mSUGRA value for large values of m_ϕ, to quite small values when m_ϕ becomes less than zero[20]. In particular, when $m_A \sim 2m_{\widetilde{Z}_1}$, then neutralinos in the early universe may annihilate efficiently through the A and H Higgs resonances, so that again $\Omega_{CDM}h^2$ may be brought into accord with the WMAP determination. In

[1] We stress that we are using $SO(10)$ considerations only to guide our thinking, and do not commit to any particular $SO(10)$ framework. As a result, many of the usual consequences such as the unification of Yukawa couplings that follow in the minimal $SO(10)$ model, no longer obtain in our case. In particular, as we will see below, it is possible to break electroweak symmetry radiatively even if the MSSM Higgs scalar doublets have equal mass parameters at $Q = M_{GUT}$.

the mSUGRA model, the A-annihilation funnel occurs only at large $\tan\beta \gtrsim 45$ (55) for $\mu < 0$ ($\mu > 0$). However, in the NUHM1 model, the A-funnel region may be reached even for low $\tan\beta$ values, if m_ϕ is taken to have negative values. At low $\tan\beta$, the A and H widths are much narrower than the large $\tan\beta$ case. We also show in frames b) the relic density Ωh^2, c) the branching fraction $BF(b \to s\gamma)$ (allowed range conservatively taken to be $\sim (2.6-4.5)\times 10^{-4}$), and d) the SUSY contribution to the muon magnetic moment Δa_μ. We have also checked that the branching ratio $B(B_s \to \mu^+\mu^-) < 10^{-8}$ even for the smallest values of m_A in Fig. 1.

To understand the behavior of the μ parameter and m_A in the NUHM1 model, we define $\Delta m^2_{H_{u,d}} \equiv m^2_{H_{u,d}}(\mathrm{NUHM1}) - m^2_{H_{u,d}}(\mathrm{mSUGRA})$, and obtain the one loop renormalization group equation

$$\frac{d\Delta m^2_{H_u}}{dt} \simeq \tfrac{2}{16\pi^2} \times 3 f_t^2 [X_t(\mathrm{NUHM1}) - X_t(\mathrm{mSUGRA})] \simeq \tfrac{3}{8\pi^2} f_t^2 \Delta m^2_{H_u}, \quad (2)$$

where $t = \log(Q)$, f_t is the top quark Yukawa coupling, and $X_t = m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2$. Eq. (2) can be readily integrated to obtain,

$$\Delta m^2_{H_u}(weak) = \Delta m^2_{H_u}(GUT) \times e^{-J_t}\ ,$$

where $J_t = \frac{3}{8\pi^2}\int dt f_t^2 > 0$. We see that $\Delta m^2_{H_u}$ maintains its sign under RG evolution, and furthermore, reduces in magnitude in the evolution from high to low scales. The same considerations also apply to $\Delta m^2_{H_d}$, except that the effect is much smaller because for the modest values of $\tan\beta$ that we consider, $f_{b,\tau} \ll f_t$ so that J_b and J_τ are both $\ll 1$ and $\Delta m^2_{H_d}(GUT) \simeq \Delta m^2_{H_d}(weak)$. From the tree level minimization condition for EWSB in the MSSM

$$\mu^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2},$$

we see that for moderate to large values of $\tan\beta$ (as favored by LEP2 Higgs boson mass constraints), and $|m^2_{H_u}| \gg M_Z^2$, $\mu^2 \sim -m^2_{H_u}$. We thus see that a large value of μ^2 is expected if m_ϕ is large and negative. In contrast, for $m_\phi > m_0$, we expect a smaller weak scale magnitude of $m^2_{H_u}$, and hence of μ^2.

The tree level pseudoscalar Higgs mass m_A is given by

$$m_A^2 = m^2_{H_u} + m^2_{H_d} + 2\mu^2 \simeq m^2_{H_d} - m^2_{H_u},$$

where the last equality holds in the approximation $\mu^2 \sim -m^2_{H_u}$. For values of $\tan\beta$ such that J_b and J_τ can be neglected compared to J_t, it is easy to see that

$$m_A^2(\mathrm{NUHM1}) - m_A^2(\mathrm{mSUGRA}) = (sm_\phi^2 - m_0^2)(1 - e^{-J_t})$$

thereby accounting for the m_A dependence in Fig. 1a.

Most other sparticle masses are relatively invariant to changes in m_ϕ (justifying our approximation in the last step of (2)). An obvious exception occurs for the chargino $\widetilde{W}_1$ and neutralino $\widetilde{Z}_{1,2}$ masses, which become small when $\mu \lesssim M_{1,2}$, and the $\widetilde{Z}_1$ becomes increasingly higgsino-like. The other exception occurs for third generation squark masses. In this case, the $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ running masses depend on m_ϕ via the $f_t^2 X_t$ terms in the RG equations, and can be somewhat suppressed for large positive values of m_ϕ^2.

In order to estimate the dark matter detection rates for the NUHM1 model, we adopt a cored halo model (the Burkert profile, [21]) which has been tested against a large sample of rotation curves in spiral galaxies [22], and whose density profile reads

$$\rho_B(r) = \frac{\rho_B^0}{(1 + r/a)\,(1 + (r/a)^2)}, \quad (3)$$

with $a = 11.7$ kpc and $\rho_B^0 = 0.34$ GeV cm^{-3}. The particular configuration we use has been found after implementing all available dynamical constraints and numerical simulation indications on the halo mass-concentration correlation [23]. The corresponding velocity distribution has been self-consistently computed (see Ref. [23] for details), thus allowing for a reliable comparison among direct and indirect detection techniques [24].

Following Ref. [24, 25], we adopt here *Visibility Ratios* (VR), *i.e.* ratios of the expected signals from a given supersymmetric model over the projected future sensitivities in the particular detection technique, and for the corresponding neutralino mass. Direct detection refers to the spin-independent (SI) neutralino-proton scattering cross section, compared to the sensitivity of CDMS-II[26] and of future ton-size experiments, such as XENON [27]. We compute the flux of neutrino-induced muons produced by neutralino pair annihilations in the sun, and compare the flux against the projected sensitivity of the km^2-size detector IceCube (computed for an energy threshold of 1 GeV), taking into account the energy threshold mismatch and the dependence of the detector sensitivity on the soft (*e.g.* $b\bar{b}$, in the left panel of Fig. 2) and hard (*e.g.* W^+W^-, in the right panel of Fig. 2) neutrino production channels, following Ref. [28]. As regards antideuterons, we compute the solar-modulated flux, at solar maximum, in the low energy range $0.1 < T_{\overline{D}} < 0.4$ GeV, where the background is strongly suppressed [29]. The VR is then defined as the ratio of the computed $\overline{D}$ flux over the sensitivity of a GAPS [30] detector placed on a satellite orbiting around the Earth, and tuned to look for antideuterons in the mentioned very low kinetic energy interval, corresponding to a $\overline{D}$ flux of $2.6\times10^{-9}\mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}\mathrm{s}^{-1}$ [30]. Regarding antiprotons and positrons, we adopt the quantity I_ϕ, defined in Ref. [24], and examine the sensitivity of the PAMELA experiment after 3 years of data-taking. Finally, the gamma ray flux from the galactic center (GC) refers to the sensitivity of the GLAST experiment to the

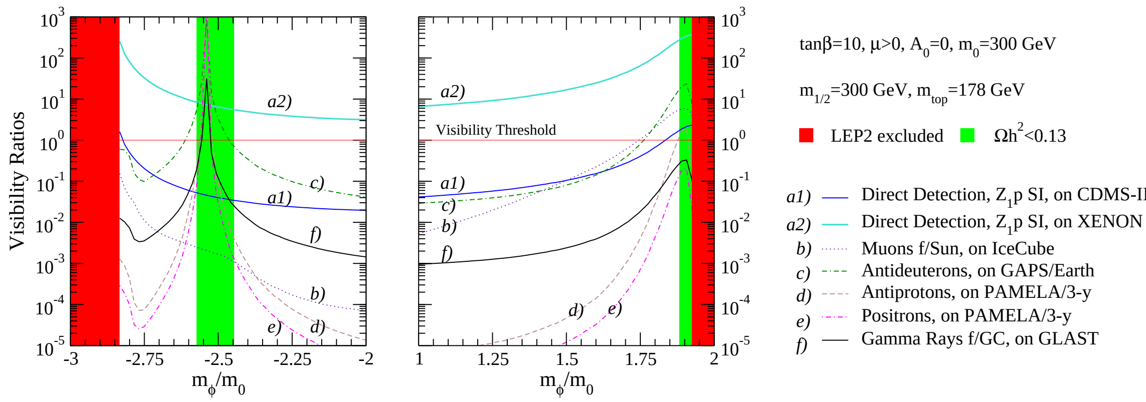

FIG. 2: Dark matter detection Visibility Ratios (*i.e.* signal-to-projected-sensitivity ratios) for various direct and indirect techniques, as a function of the GUT-scale non-universal Higgs mass parameter m_ϕ. A Visibility Ratio larger than 1 implies that the model will be detectable. The dark (red) shadings to the left (right) of the plot indicate regions ruled out by the LEP2 bounds on m_A ($m_{\widetilde{W}_1}$). Within the lighter shaded (green) regions a thermal neutralino relic abundance compatible with the WMAP upper bound [2] is produced.

integral photon flux above a 1 GeV threshold [31].

While only large values of m_ϕ will be probed via CDM detection at CDMS-II, all the parameter space will be probed by future experiments such as XENON. Interestingly enough, we obtain observable rates for indirect detection experiments only in those regions where a neutralino relic abundance compatible with the WMAP upper bound [2] is produced. The first cosmologically allowed parameter space region, lying in the range $-2.57 < m_\phi/m_0 < -2.45$, features a large neutralino annihilation cross section, due to the proximity of heavy Higgs resonances[32]. This yields detectable rates in all experiments apart from IceCube, where the rate of neutralino capture inside the sun depends critically on the spin-dependent neutralino-nucleon coupling, which is suppressed in this large $|\mu|$ region: see Fig. 2. In the second viable parameter space region ($1.83 < m_\phi/m_0 < 1.93$), a large higgsino fraction implies instead detectability at IceCube, as well as at future antiprotons and antideuterons searches. Though positrons and gamma rays rates are enhanced in this region, they will still be slightly below the respective planned experimental sensitivities. We note, however, that detection rates from halo annihilations are very sensitive to the CDM halo profile which is assumed. More quantitatively, we find that with an extremely cuspy profile (such as the adiabatically contracted NFW profile of Ref. [23]), the direct detection and neutrino telescope rates increase only by around 20%, the $\overline{D}$ flux by $\sim 10^1$, positrons and antiprotons VR's by $\sim 10^2$, and the gamma ray flux from the GC by more than 10^4 (see also the discussions in Ref. [32] and [24]).

Summary: The mSUGRA model prediction of the CDM relic density can be brought into accord with the WMAP measured value only if the neutralino annihilation cross section is enhanced, usually due to A and H boson resonances, or by increasing the higgsino content of the neutralino. Within the mSUGRA framework, these possibilities occur only if $\tan\beta$ is very large or scalar masses are in the HB/FP region at very large m_0. We have shown that in the NUHM1 model, a well motivated 1-parameter extension of mSUGRA, neutralino annihilation via heavy Higgs resonances can occur even for low values of $\tan\beta$, and neutralino annihilation via higgsino components can occur at low values of m_0. Thus, a much wider range of collider signals and low energy phenomenology is possible compared to expectations from the mSUGRA model.

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